Risk Informed Design of Offshore Wind Turbine Structures in the U.S. Outer Continental Shelf

Timothy Wade Cook

ABSTRACT

The United States has enormous potential offshore wind energy resources in the Atlantic, Pacific, Great Lakes and the Gulf of Mexico. However, progress in developing these resources has lagged behind that in Western Europe and no offshore wind farms have been built to date in the U.S. Continental Shelf. Uncertainties in U.S. siting and design criteria, specific regulations and standards, along with a lack of experience have challenged development by increasing both cost and the time to deployment. The reliability of offshore wind turbine farms is critical to industry success and should be secured efficiently with respect to cost. The ability to employ probabilistic risk management and decision theory in the design process of support structures would afford more transparent system reliabilities and more flexibility in design compared with prescriptive design standards. A general framework for risk informed design of offshore wind turbine structures is demonstrated on a typical monopole support structure. The structural parameters are manipulated to adjust the risk and to achieve the desired wind turbine performance at acceptable cost. In order to implement such a design procedure in practice, regulations must stipulate clear performance requirements in terms of system reliability for project approval.

INTRODUCTION

In order to meet future energy demands, the United States (U.S.) will have to not only test its ability to tap current known exhaustible energy sources but also expand and transition its energy portfolio to renewable energies.

Although the U.S. does not have any installed wind farms offshore to date, there are a number of proposed projects in various stages of approval, the most notable being the Cape Wind Project, a proposed 130-turbine offshore wind farm planned for Nantucket Sound off the coast of Massachusetts (Transportation Research Board (TRB), 2011). Developers of the project have been seeking approval for 10 years; in 2011, Cape Wind became the first offshore wind farm project approved in the U.S. by both state and federal governments. This landmark approval reflects both the determination of the project developers as well as recent legislative action favoring offshore wind development. To invigorate the development of renewable energy portfolios, the U.S. Department of Energy (DOE) recently published an ambitious initiative which aims for 20% of U.S. energy to be supplied by wind power (54 gigawatts from offshore) by 2030, with an interim goal of 10 GW offshore by 2020. In order to ensure successful deployment of the offshore wind industry the DOE identified two critical objectives: reducing the cost of energy and reducing the time to deployment (DOE, 2010).

There are many reasons why offshore wind farms are attractive when compared with onshore farms despite their higher initial capital cost, including favorable wind climatology, ability to upscale (increase utilization) and proximity to power demand.

Offshore, the wind is more consistent and the wind velocity is greater at lower elevations. Construction on the water allows larger structures that are not challenged by some onshore constraints (i.e. highway transportation). Moreover, the 28 Coastal and Great Lakes states account for 78% of the national energy demand. Also, the major cities located in these states generally pay higher costs of energy, further conducing the utility and cost competitiveness of strategically sited offshore wind farms (DOE, 2010).

The outer continental shelf (OCS) of the U.S. has the potential to provide 2,957 GW of gross (neglecting siting constraints) available offshore wind energy within 50 miles of shore, which translates to approximately 3 times the current capacity of the national grid (TRB, 2011). The U.S. is well positioned with the resources and the means currently available to become a leader in offshore wind technology and utilization.

The offshore wind industry is challenged by the uncertainties inherent in any nascent industry/technology. In order to compete against other energy sources (which may be subsidized and already benefiting from the economies of scale), offshore wind energy must be deliverable at a relatively attractive cost. To achieve cost goals, offshore wind facilities need to be highly reliable and durable (DOE, 2011). Offshore wind farm reliability is key in securing financing, insurance, social acceptance, market contracts and safety for both long-term and short-term perspectives.

Quantitative reliability assessments of an engineered system involve considering the probability that a system will successfully meet defined performance criteria for a defined period of time. Adopting a consistent probabilistic design framework, in which the uncertainties and the reliability of the design are transparent to the designer, allows the engineer to incorporate and optimize with respect to project-specific risks and produce comparable designs. While risk-informed design may require a higher level of competency by the engineer than traditional prescriptive methods, offshore wind turbine design is particularly well suited to benefit from a project-specific risk-informed design approach. For example, the design phase of an offshore wind turbine involves less than 4% of its lifecycle cost (DOE, 2010), and the presence of current uncertainties in the design process challenging the predictability of cost and reliability estimations may significantly influence total costs. Additionally, offshore wind turbines are designed in groups for a particular wind farm and have relatively little variability in structural configuration, thus facilitating even larger capacity for refining and updating reliability design and analysis methods compared with most civil engineering projects, which are typically unique.

STUDY OBJECTIVES

The objectives of this study project are two fold:

1) To introduce the concept of a risk-informed approach to performance assurance of offshore wind turbines located in the U.S. OCS, and
2) To demonstrate a general framework for risk-informed design of offshore wind turbine support structures with respect to a target level of reliability.

Basic reliability principles are introduced and a reliability analysis and design of a monopole support structure is performed based on an assumed acceptable level of risk to illustrate the concepts.

METHODS

Elements and Application of Risk-Informed Approach to Performance Assurance

The offshore wind industry is challenged by a lack of empirical observations or historical benchmarks from which to derive experience-based design criteria. Many agencies and countries, primarily European, have developed comprehensive yet largely prescriptive standards, and none are applicable, without significant modification, in the U.S. (TRB, 2011). In general, development of a risk informed basis for structural design requires:

- Definition of structural components and groups
- Identification of important failure modes or limit states for components and systems
- Stochastic models for uncertain parameters
- Quantified performance goals (i.e. acceptable reliability level)
- Standardized method and assumptions for reliability calculation
- Risk-consistent design criteria to achieve the performance objectives

Reliability-based Formulation of Design Criteria

In order to design for adequate performance, system requirements can be translated into so-called limit state conditions from which equations can be developed that separate the acceptable region of performance from what is considered the failure region. Defining the demand, S, and the capacity, R in a structural system, a safety margin, M, can be defined as:

$$M = R - S \tag{1}$$

A positive M in Eq. 1 represents adequate performance and a negative value represents failure. In the presence of uncertainty, R and S are random variables, and their uncertainties are modeled by their probability distributions. The failure condition, or limit state, is defined by the inequality of M being less than zero because the demand exceeds the capacity (R) of the system. Given probabilistic descriptions of R and S, the probability of failure, Pf, can be determined as:

$$P_F = P[M < 0] = P[R - S < 0] \quad (2)$$

The probability of failure can be viewed as a risk metric, the complement of which is known as reliability. Thus, design for a stipulated value of Pf provides the basis of risk-based design. For example, the design parameters of the support structure or tower could be adjusted to achieve a target reliability allowing for economical and optimal design solutions by balancing decisions based on material consumption, performance requirements, failure consequences and probability of failure for each group/component (Sorensen & Toft, 2010). Note that Pf is a subjective measure, in the sense that it is dependent on the information available and the engineering models and assumptions used in performing the calculation. Thus consistent reliability analysis methods and assumptions are critical, and the reduction of uncertainties in engineering models allows for better reliability estimates.

Example Development: Reliability-Based Design of Monopole Turbine Support

To demonstrate the general concepts, we consider a typical monopole structure modeled to support a 5 MW turbine off the east coast of the U.S. (see Figure 1). The structural elements for the monopole include the pile and the tower. For simplicity, the wind turbine is assumed to be parked and the only limit state considered is the onset of yielding in the pile due to an overturning moment (OTM) from a combination of actions due to wind, wave and current. The wind turbine is modeled to represent the NREL 5 MW baseline turbine defined by Jonkman, et al (2009) with a yaw misalignment of about 8 degrees. The site and environmental conditions were extracted from MMI Engineering (2009), and the support structure was developed to be comparable to the monopole defined in that report. The environmental conditions reflect data consistent with siting south of Massachusetts and Rhode Island between Martha's Vineyard and Block Island, and the water depth is assumed to be 25 meters.

Thus, given:

1. Structural elements and configuration
2. Proposed site and stochastic description of hazards and environment
3. Definition of limit state
4. Assumed target level of reliability: Pf-target = 10-4 per year (DNV, 2007; TRB, 2011)

We seek the following goals:

1. More transparent structural system reliability
2. Ability to employ probabilistic risk assessment and managemen procedures when adjusting structural parameters

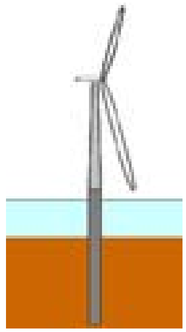

Figure 1. Typical Monopole Offshore Wind Turbine Structure.

PROCEDURE AND MODELS

Structural Reliability Analysis and Design Procedure

The primary engineering analysis tools used for this project included MATLAB, GTSTRUDL and GTSELOS. MATLAB's random number generation capabilities were utilized to simulate 100 random independent environmental conditions (i.e. wind-wave-current parameters) and to perform the reliability analysis using Monte-Carlo simulation methods. GTSTRUDL was used for structural analysis and evaluating structural response, while GTSELOS was used to calculate the structural demand from combinations of wind-wave-current. Figure 2 demonstrates the general procedure followed in a simple flow chart.

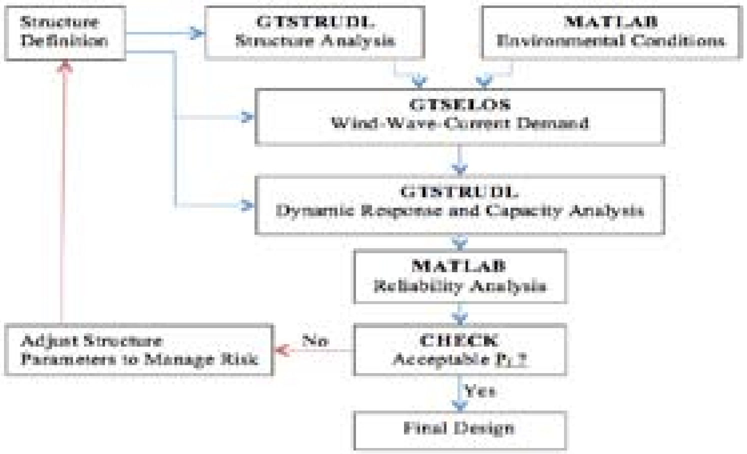

Figure 2. Flow chart of reliability-based design procedure.

Turbine Model

Only parked turbine conditions are considered. For simplicity, the NREL 5 MW baseline turbine is modeled as a point mass at the top of the support tower. An equivalent flat plate area of 292 m2 was estimated from loads data calculated for this turbine published by the American Bureau of Shipping (ABS, 2011) to model the viscous drag forces on the parked rotor nacelle assembly (RNA), assuming an overall drag coefficient Cd=1.28. This is assumed to represent roughly an 8 degree yaw misalignment. It is noted that the magnitude of the drag loads on the RNA are sensitive to the degree of yaw alignment (ABS, 2011).

Support Structure Model

The support structure defined in this report consists of two components: the pile and the tower. The pile is a single diameter extending from the penetration depth (60 m below mud line) to 10 m above the mean water level. To model a tapered tower, the tower defined in this report consists of 20 equal-length pipe segments with incrementally decreasing diameters and thicknesses from bottom to top. Consistent with common practice, the preliminary design of the support structure conforms to a target natural frequency range of 0.20 to 0.34 Hz to avoid resonance with the rotor and blade passing frequencies of the turbine in operating conditions (MMI, 2009). The initial structural model has a natural frequency of 0.241 Hz. Structural damping of all modes was assumed to be 1%. The tower and initial pile properties are defined in Table 1.

Table 1. Initial Pile and Tower Properties

Property	Pile	Tower
Base Diameter (m)	6. 5	6
Base Thickness (m)	0. 065	0. 03
Top Diameter (m)	6. 5	3. 78
Top Thickness (m)	0. 065	0. 019
Total Length (m)	95	77. 6
Density (kg/m3)	8500	8500
Damping Ratio	1%	1%
Young's Modulus, E (GPa)	210	210
Shear Modulus (GPa)	80. 8	80. 8

The specified steel density supplied by NREL (8500 kg/m3) is larger than typical steel values to account for paint, welds, and flanges (Jonkman et al., 2009). The pile is assumed to be an open tube driven to the target penetration depth with the interior filled to the mud line with soil. Pile-soil interaction is modeled using horizontal and vertical linear soil springs, estimated from soil spring data assumed by MMI (2009). The mass of the soil inside the pile is modeled as a uniform added inertia mass in the horizontal direction based on an assumed soil density of 18 kg/m^3. The structural model can be seen in Figure 3.

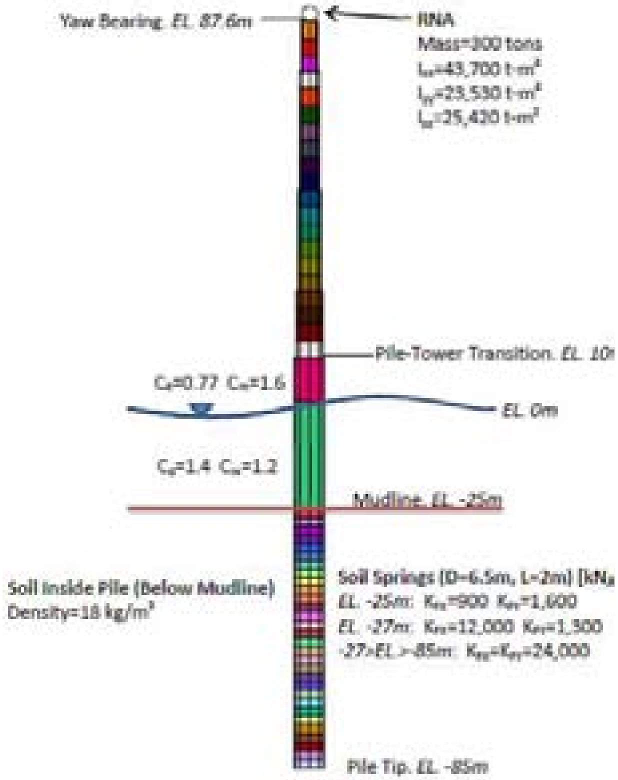

Figure 3. Support Structure Model

Environmental Load Data

The wind turbine structure is assumed to be set on a flat sea bed. The only environmental load conditions considered in this study are effects of wind, wave and current. Data supplied by MMI (2009) including scattergrams of:

- Wind speed (10m, 1hr mean), U10m,1hr vs. Significant wave height, HS
- Significant wave height, HS vs. Average zero-crossing wave period, TZ
- Maximum wave height, HMAX vs. HS

Along with 4 extreme storm conditions was used to estimate wind-wave-current condition parameters and statistical descriptions. A Gumbel (Type 1) distribution was used to model

U10m,1hr as shown in Figure 4 with location and scale parameters determined to be 15.28 and 7.95 respectively.

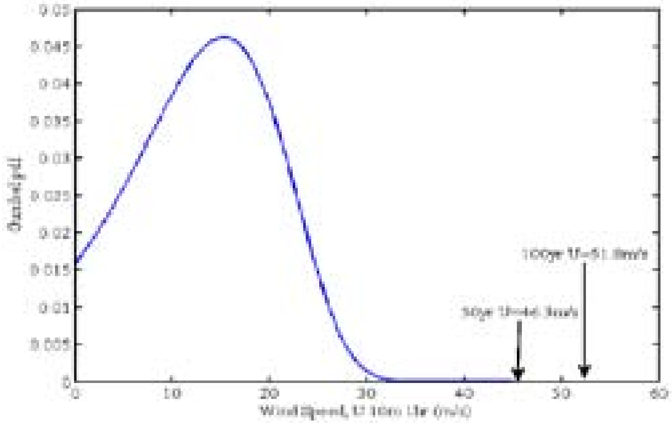

Figure 4. Defined Gumbel probability density function of annual maximum wind speed

The 50- and 100-year markers in Figure 4 indicate the annual maximum wind speeds with a 50-year and 100-year return period, respectively. The relation between U10m,1hr and the mean significant wave height, HS-mean, is shown by the best-fit power relation in Figure 5, which is based on selected average points from referenced scattergrams and extreme storm states.

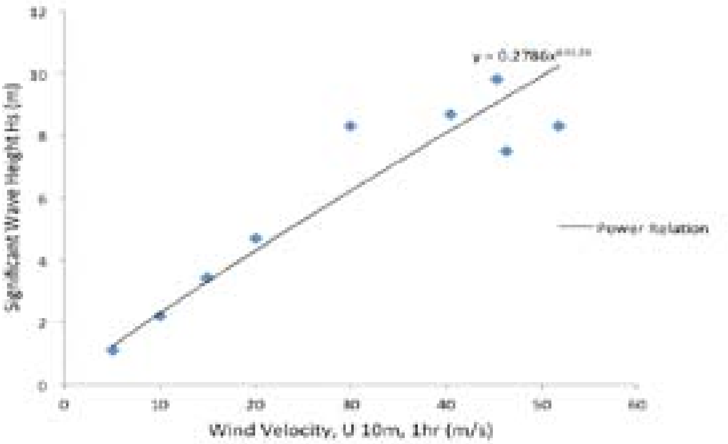

Figure 5. Relationship for HS-mean and U10m,1hr

From HS-mean, a random value for HS was generated with the assumption of a normal distribution about the mean and a modified standard deviation of 0.434 to account for an apparent 85% correlation between U10m,1hr, and HS observed in the referenced data. The 100 environmental events were simulated by generating random values of U10m,1hr and corresponding values of HS. The deterministic relationships for the remaining parameters are shown below.

$$H_{MAX}{}^{*} = 2.144 H_S^{0.8719} \quad (3)$$

$$T_2{}^{*} = 4.29 H_S^{0.3512} \quad (4)$$

$$T^{*} = 1.2 T_2 \quad (5)$$

$$C_S = 0.0091 U_{10m,\ 1hr} \quad (6)$$

Note that the designation * indicates a relationship defined by MMI (2009).

Wind Demand

An empirical power law description of the wind speed profile shown in Eq. 7 was assumed with an exponent of 0.11 for extreme wind conditions, as suggested by IEC 61400-1 (2005).

$$U(z) = U_{10m,\ 1hr} \left(\frac{z}{10m}\right)^{0.11} \quad (7)$$

in which z is the height above mean sea level. Wind viscous drag forces were calculated by Eq. 8:

$$F_D = \tfrac{1}{2} \rho V^2 C_D A_{proj} \quad (8)$$

where

V is the wind velocity (m/s)

$C_D = 0.5$ (cylinder)

A_{proj} is the projected area of the surface (m)

$\rho = 1.225$ (kg/m3)

Wave and Current Demand

Structural demands due to waves were calculated by GTSELOS using 5th Order Stokes Wave Theory. For simplicity, maximum breaking wave height and wave slam are not considered in this study. The values for the drag and inertia coefficients are consistent with MMI (2009). The current velocity at depth z, C(z), is defined as:

$$C_{(z)} = C_s \left(\frac{h_0 - z}{h_0}\right) \quad (9)$$

in which h0=50m is the reference depth for wind-generated current (DNV, 2007).

RELIABILITY ANALYSIS RESULTS AND DESIGN

Structural Demand, S

The 100 random environmental conditions were input as parameters for load calculation in GTSELOS and the maximum overturning moment (OTM) in the pile due to the applied loads was determined in GTSTRUDL. A Gumbel distribution was chosen to model the max OTM demand (see Fig. 6) because it is a common distribution type for modeling intensities due to maximum extreme environmental events (Ang & Tang, 2006). The distribution parameters (location and scale factor) were estimated by determining a best-fit line of the data assembled on a Gumbel probability plot.

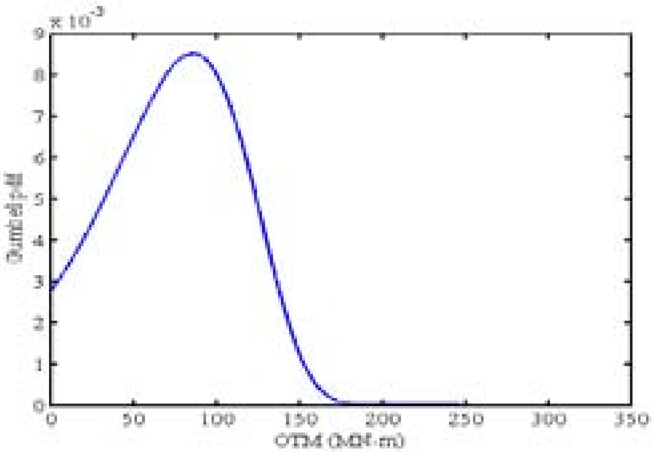

Figure 6. Gumbel probability density function of maximum annual OTM demand, S, for initial structure

Structural Capacity, R

The capacity, in terms of OTM, of the structural model was determined by incrementally increasing four extreme event storms and identifying the OTM values when the defined limit state was reached. The average was taken to be the nominal capacity, OTMnom, which was 587.7 MN-m. The mean value of yield strength of typical construction grades of steel is approximately 10% higher than the specified nominal yield strength, while the coefficient of variation of a fabricated shape would be approximately 12% (Ellingwood, 2000). Thus, the mean OTM capacity, OTMcap, was assumed to be 10% larger than OTMnom, or 646.5 MN-m. A lognormal distribution and a coefficient of variation equal to 12% was assumed to describe the OTM capacity as shown in Figure 7.

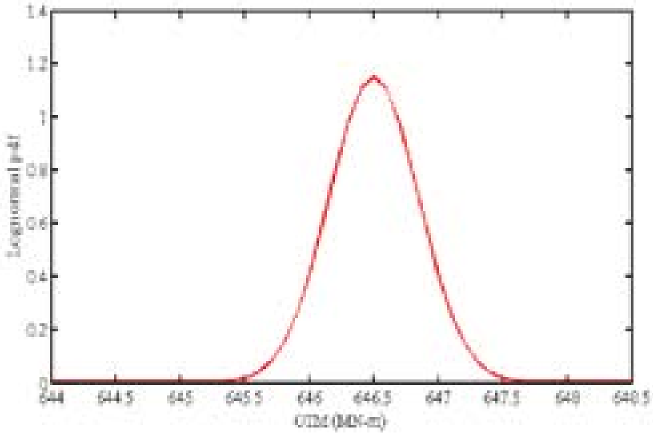

Figure 7. Lognormal probability density function of OTM resistance, R, for initial structure

Reliability Analysis and Check

A Monte Carlo simulation method was used for reliability calculations. With the estimated S and R distributions of the wind turbine support structure defined, 25 million random samples were taken from S and R, and the probability of failure was quantified by the ratio of the number of samples for which M was less than zero divided by the total number of samples. The probability of failure of the initial structure, Pf-1, was calculated to be 2.1x10-6 per year. Although Pf-1 is less than Pf-target, implying the risk is less than the level stipulated for design, an efficient design would have a Pf less than but near Pf-target¬ so the structure is not unnecessarily expensive in terms of cost and materials etc.

Design and Risk Modifications

Given the environmental conditions, structure configuration, and turbine, the design engineer can adjust the risk associated with failure induced by OTM, for example, by adjusting the OTM capacity (i.e. altering pile thickness, diameter, or selecting an alternate strength steel). To demonstrate the concept, it is assumed that decreasing the pile thickness is the most beneficial approach to increasing the risk to be nearer the target level. Thus, the pile thickness was reduced from 6.5 cm to 5 cm below the mud line. The natural frequency of the modified structure was 0.234 Hz, which remains within the target range. The analysis procedure was repeated with the same assumptions and the probability of failure of the modified structure, Pf-2, was calculated to be 3.1x10-4 per year, which is close to Pf-target and completes the risk-based design procedure.

CONCLUSIONS AND FUTURE DEVELOPMENT

Offshore wind turbine development, particularly in the U.S., would benefit from standardized risk informed design procedures. A general framework for risk informed design has been demonstrated on a typical monopole support structure sited on the U.S. OCS. Given consistent reliability analysis methods and assumptions, the Pf can be used as a risk metric for adjustment of design parameters with respect to cost to achieve an acceptable level of reliability. Examples of helpful methods and assumptions to be developed include region-specific statistical distributions for environmental parameters, recommended methods for determining distribution parameters, and consistent structural modeling assumptions. Additionally, in order to implement such a design procedure, regulations would need to define clear performance requirements (i.e. a P¬f-target) for project approval. As the industry is just being deployed in the U.S., regulators and standards organizations have the opportunity to endorse a risk informed design basis from the very beginning.

ACKNOWLEDGEMENTS

This report was developed as part of an undergraduate independent study project. The author is deeply honored to have had the opportunity to study and grow under the advisement of Dr. Bruce R. Ellingwood. His unsurpassed advice and expertise in structural reliability, risk assessment, and standards development proved invaluable and enlightened the author. Special thanks are also due to Dr. Emkin for providing software critical to the project, GTSTRUDL and GTSELOS.

REFERENCES

American Bureau of Shipping (ABS). (2011). Design Standards for Offshore Wind Farms. 2, 79-90.

Ang, A.H.-S & Tang, W.H. (2006). Probability Concepts in Engineering: Emphasis on Applications to Civil and Environmental Engineering. John Wiley & Sons. ISBN 047172064X

Det Norske Veritas (DNV). (2007). Offshore Standard DNV-OS-J101 Design of Offshore Wind Turbine Structures. Oslo, Norway.

Ellingwood, B. (2000). LRFD: implementing structural reliability in professional practice. Engrg. Struct. 22(2):106-115.

International Electrotechnical Commission (IEC). (2005). IEC 61400-1 Ed. 3, Wind Turbines – Part 1: Design requirements.

Jonkman, J. M., Butterfield, S., Musial, W. & Scott, G. (2009). Definition of a 5-MW Reference Wind Turbine for Offshore System Development. National Renewable Energy Laboratory, Golden, Colorado, Report No. NREL/TP-500-38060

MMI Engineering Inc. (2009). Comparison of API & IEC Standards for Offshore Wind Turbine Applications in the U.S. Atlantic Ocean: Phase II. MMI Project No. MMW554.

U.S. Department of Energy (DOE). (2010). Creating an Offshore Wind Industry in the United States: A Strategic Work Plan for the Unites States Department of Energy, Fiscal Years 2011-2015.

U.S. Department of Energy (DOE). (2011). Offshore Resource Assessment and Design Conditions Public Meeting – Summary Report. Wind and Water Power Program Energy Efficiency and Renewable Energy, U.S. Department of Energy.

Sorensen, John D., & Toft, Henrik S. (2010). Probabilistic Design of Wind Turines. Energies 2010, 3, 241-257; doi:10. 3390/en302024

Transportation Research Board (TRB). (2011). Structural Integrity of Offshore Wind Turbines; Oversight of Design, Fabrication, and Installation. Transporation Research Board of the National Academies. Washington, D.C. 20001. Special Report 305.